IMPROVING CARBON ESTIMATION OF LARGE TROPICAL TREES BY LINKING AIRBORNE LIDAR CROWN SIZE TO FIELD INVENTORY

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ABSTRACT

Quantifying tropical aboveground biomass (agb) is an outstanding challenge that requires knowledge on the 3D structure of forests. Recent studies suggest that the uncertainty in estimating agb of large trees is significantly reduced if tree height and crown size are accounted for in addition to the traditional trunk diameter and wood density. Due to the fact that field inventory techniques are not adapted to characterize the 3D forest structure, crown size metrics (e.g. height and radius) are commonly estimated as a function of trunk diameter using allometric models with limitations in explaining crown variability. Airborne lidar techniques have the potential for characterizing tree height and crown size but are not adapted to estimate trunk diameter, which is a strong predictor of agb.

Here, we investigate the synergy of field inventory and airborne lidar techniques to characterize the forest structure by assessing the uncertainty introduced by the field-based allometric models in the estimation of agb at the tree-level. We focus in 1454 large individual trees (trunk diameter > 60 cm) located within the La Selva Biological Station for which we dispose of field observations (trunk diameter and wood density) and lidar derived metrics (tree height and crown radius). We show that the field-based allometric models overestimate tree height and underestimate crown radius. As a result, the allometric approach overestimates the tree-level agb in 0.8 Mg when considering the 1454 individuals and the errors can reach more than 50% of the agb of individual trees. These errors on the large trees agb highly impact on the plot-level results and then propagate to the estimation of carbon stocks at the regional and national-levels.

Index Terms— aboveground biomass, uncertainty, tree allometry, large trees, La Selva Biological Station, airborne lidar, individual tree crown

1. INTRODUCTION

Plot-level aboveground biomass (agb) estimates are still the bedrock for the calibration and validation of national and global remote sensing models [1]. The uncertainty associated with existing field-derived agb estimates propagates to broad-scale extrapolations and therefore to the landscape- and national-level agb maps [2]. Recent studies suggest that tree-level carbon stocks uncertainty is significantly reduced if we consider tree height (th) and crown radius (cr) in addition to the traditional metrics that are commonly acquired using field inventory techniques, namely trunk diameter (td) and wood density (wd) ([3], [4]). However, the use of th and cr over tropical forests has been limited by the scarcity of data because both metrics are difficult to measure from the ground in closed-canopy forests with large uncertainties associated. Alternatively, models involving only td and wd have been preferred [5]. Other researchers derived th and cr by means of allometric models calibrated using a few individuals that are located within limited areas. In summary, the 3D forest structure greatly impacts the agb spatial variability but field-based techniques are not optimal to characterize tropical forests canopy. The use of allometric models (e.g. td-th, td-cr relationships) limits our knowledge on current tropical biomass stocks because they are not able to fully describe the tree height and crown size variability.

In this work, we assess the uncertainty associated with tree-level agb estimates introduced by the limitation of field inventories to describe the 3D forest structure and the use of allometric models. We link field-derived metrics (td and wd) to lidar measurements (th and cr) at the individual tree-level over the La Selva Biological Station. Then, we compare results for two different agb estimation approaches. In the first one, both td and wd are provided by the field inventory, whereas th is calculated using a local td-th allometric model. In the second approach, the th is derived from airborne lidar-derived individual trees. We compare the ability of field-based allometric models and lidar-derived individual trees to characterize the crown size variability and the impact on the estimation of agb at the tree level.

We focus on large trees only (td>60 cm) for two main reasons. First, lidar-derived individual trees are difficult to link to field measurements due to the high tree density in tropical environments. Second, large trees store most of the agb in the tropics and they dominate the landscape agb variability [6]. Systematic errors associated with large trees agb estimates are expected to disproportionally propagate to plot-level predictions because of their prominent contribution to plot agb. Accurately estimate agb for large trees is a prerequisite for improving local estimations that limit the risk of uncontrolled error propagation to broad-scale extrapolations using remote sensing data [2]. Moreover, recent studies suggest that landscape-level agb can be predicted from a few large trees over certain tropical environments [7].

2. MATERIAL

The study area is located in the Atlantic lowlands of Costa Rica in the La Selva Biological Station, which is one of the most extensively studied field sites in tropical forests with a well-documented history of its biological datasets. The area receives an annual rainfall of 4000 mm and has a mean temperature of 26º C. It has a mixture of old growth and secondary lowland tropical forest wet forest along with remnant plantations and various agroforestry treatments.

The field data used in this work correspond to old grown forest only. We recorded the location, species and tree diameter of 1454 large trees (td > 60 cm) within the La Selva perimeter (red dots in Figure 1). The species identification allows us to determine its wd. The tree location was calculated using a handled GPS device without post-processing. Due to strong obstruction of GPS signal under old growth canopy errors in geolocation can reach more than 20 meters.

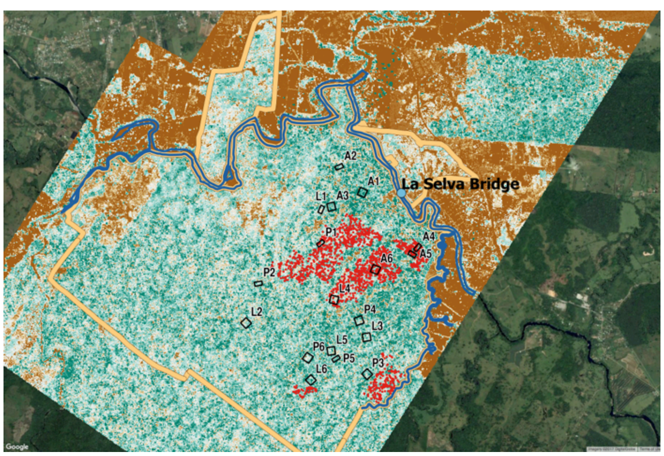

Figure 1. Study area over the La Selva Biological station (yellow polygon). The red dots represent the location of the large trees. The research plot locations (black polygons) and the Puerto Viejo river (blue line) are also show for the purpose of visualization.

Then, to calculate the td-th relationship we used a field inventory dataset collect in the year of 2009 and 2016 over 18 inventory plots (black polygons in Figure 1). In the campaign of 2009, all trees (td > 10 cm) have been measured, whereas in the year of 2016 we followed a sampling strategy. Briefly, we first define five groups of td classes: group 1 (td>70 cm), group 2 (70>td>50), group 3 (50>td>30), group 4 (30>td>20) and group 5 (20>td>10). Then, we measured a tree from group 1 and its closest tree from group 2, followed by a tree from group 1 and its closest from group 3, followed by a tree from group 1 and its closest from group 4 and, a tree from group 1 and its closest from group 5. We stop this procedure when all trees from group 1 have been measured. Note that these plots have been monitored for many years and the trees are all tagged and ordered by tree diameter.

The Blom Corporation and Northrop Grumman Company have collected the lidar data in 2009 using an Optech ALTM 3100 scanning device. The lidar data were processed to provide geo-referenced 3D point clouds. The average point density is of 4 pts./m^2 that have been filtered to identify ground and off-ground points (TerraScan, [8]).

3. METHODS

We apply a commonly used allometric model for moist tropical forests to calculate tree-level agb as a function of wd, td and th [5]:

$$agb = 0.0509 \times wd \times (td)^2 \times th \quad 1)$$

whereas for the estiamted including cr we apply [3]

$$agb = \exp\left(a + b \times \ln(td) + c \times \ln(th) + d \times \ln(wd) + e \times \ln(cr)\right) \quad 2)$$

with a=-1.8421, b=1.4378, c=0.9379, d=1.0678 and e=0.7624. We calculate individual tree biomass using two methods: 1) using field inventory data only and 2) using field inventory data along with airborne lidar measurements on individual trees. They are called “field only” (fo) and “field plus lidar” (fl) approaches, respectively. In the first one, we use wd and td provided directly by the field inventory whereas both th and cr are estimated using a local td-th allometric model derived using the long-term monitoring research plots shown in Figure 1. In the second approach, we link the trees of the field inventory to trees calculated using a lidar-based approach called adaptive mean shift (AMS3D, Figure 2) explained in [9]. This allows to relate the td observed in the field to actual lidar-based estimates on th and cr. The matching between the field and lidar individual trees is difficult in tropical forest due to the large tree density and to the poorly geolocation accuracy of field GPS measurements compared to the lidar. Therefore, we link a given large tree measured in the field to the highest one in a neighborhood of 20 meters. We sorted in descending order both the field-measured td and the lidar-derived th and the matching trees were immediately removed from the dataset to make sure trees were not linked to more than one tree. Although errors are expected using this approach due to the fact that the largest tree does not correspond necessarily to the highest one, we believe that is a reliable approach to link the largest trees within a certain area. Note that errors are minimized because we focus in the very large trees that are not as dense as trees of smaller size.

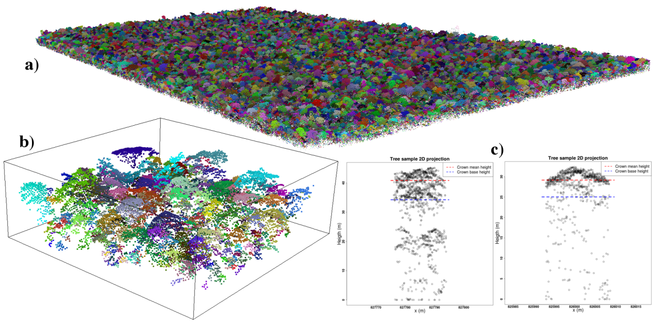

Figure 2. a) AMS3D individual tree crowns over a 2.2 km x 1.1 km area and **b)** detail over a 1-ha area. In **c)** we show an example of two individual trees.

4. RESULTS AND DISCUSSION

Figure 3 shows the allometric models (for td-th and td-cr) calibrated using the data of the 18 research plots show in Figure 1. The models are strongly correlated (r^2=0.68 and r^2=0.61, respectively).

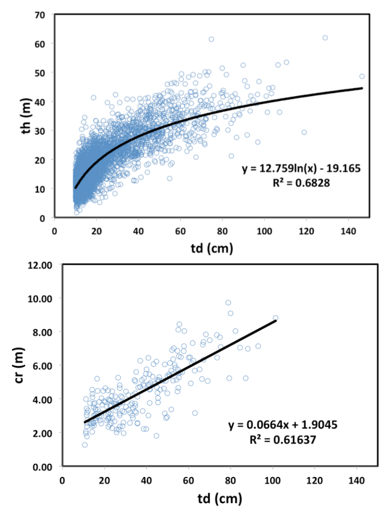

Figure 3. td-th (left) and td-cr (right) allometric models derived using the datasets collected within the research plots in the years of 2009 and 2016 and, in the year of 2016, respectively.

Figure 4 shows the field- and lidar-based characterization of th and *cr* for different td classes. As expected, it shows that the field inventory approach, that characterizes the 3D forest structure using allometric models, is unable to describe the rich height and crown size variability within tropical forests. Furthermore, the allometric model overestimates th across the entire td size spectrum but the errors are larger within the smaller classes. On the contrary, the allometric model highly underestimates cr compared to the lidar approach. This might be due to the fact that the td-cr model was established using smaller trees (td<60 cm) than the ones here under investigation Figure 3. The underestimation is of the same magnitude for all the td classes.

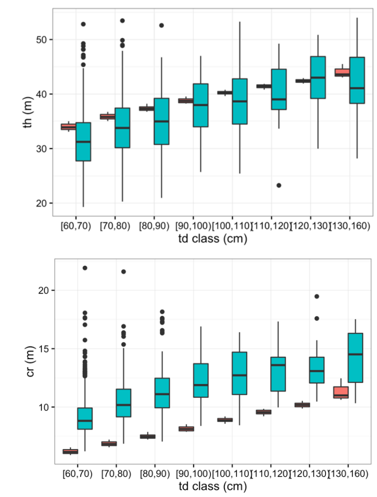

Figure 4. Box-and-whisker diagrams of tree height (th, top) and crown radius (cr, bottom) variability by td class. Orange and green colors correspond to the fo and fl approach, respectively.

Figure 5 shows the difference in estimating agb using *fo* and *fl* in terms of Megagrams (Mg) and corresponding percentage across different td classes. Positive values mean that the *fo* approach overestimates the *fl* finding.

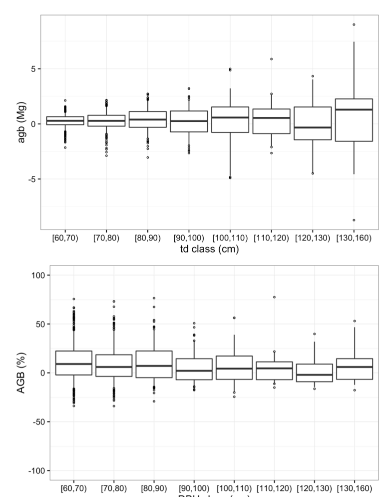

Figure 5. Box-and-whisker diagrams corresponding to the differential in agb (Mg, top) and corresponding percentage (bottom) when using fl and fo. Positive values mean that the fo approach overestimates the fl method. Main statistics are represented by the hinges (25th and 75th percentile), band (50th percentile), whiskers (5th and 95th percentiles)

The statistics corresponding to the bottom diagram of Figure 5 are show in Table 1. For instance, the *fo* approach overestimates 25% of the trees within the smallest td class by 22.3% compared to the *fl* method. In average, the *fo* method overestimates the agb.

DBH	Percentiles				
	5th	25th	50th	75th	95th
[60,70)	-16.1 (%)	-2.2 (%)	9.0 (%)	22.3 (%)	43.7 (%)
[70,80)	-15.7 (%)	-3.6 (%)	6.0 (%)	18.5 (%)	44.0 (%)
[80,90)	-14.2 (%)	-4.9 (%)	7.1 (%)	22.4 (%)	44.2 (%)
[90,100)	-13.9 (%)	-7.0 (%)	2.1 (%)	14.5 (%)	33.0 (%)
[100,110)	-19.0 (%)	-6.7 (%)	4.3 (%)	17.2 (%)	39.0 (%)
[110,120)	-11.1 (%)	-7.0 (%)	4.6 (%)	11.3 (%)	21.4 (%)
[120,130)	-14.6 (%)	-9.1 (%)	-2.0 (%)	9.0 (%)	32.0 (%)
[130,160)	-12.3 (%)	-6.6 (%)	6. 0 (%)	14.5 (%)	46.7 (%)
Average	**-14.6 (%)**	**-5.9 (%)**	**4.6 (%)**	**16.2 (%)**	**38.0 (%)**

Table 1. Statistics corresponding Figure 4b. Positive percentages mean that the *fo* approach overestimate the *fl* estimations.

However, the analysis of the absolute difference between approaches has a larger impact on the larger trees. For instance, within the [130,160) class, 25% of the trees are overestimated by the fo approach in more than 2.3 Mg, whereas another 25% are underestimated by more than 1.5 Mg. Also, the difference between approaches can reach more than 5 Mg per tree that creates a large uncertainty for a given area.

5. CONCLUSION

We show that the allometric models commonly used to describe the 3D forest structure in the framework of traditional field inventories poorly describe the forest canopy variability such as tree height and crown size. We quantify their limitation in terms of tree-level aboveground biomass estimates over 1454 large trees located in the La Selva Biological Station. As far as the tree height is concerned, errors can reach more than 50% when compared with the approach that integrates both field and lidar estimates. The average agb when considering the 1454 individuals equals 0.8 Mg. The errors on agb at the individual tree-level are up to more than 50%. The integration of airborne lidar (onboard of either an airplane or unmanned aerial vehicle) measurements with field inventory data can reduce significantly the uncertainty regarding the reference aboveground biomass baselines. This would reduce the propagation error to broad-scale estimations in order to produce more accurate landscape-, national- and global-level aboveground biomass maps to comply with the REDD requirements.

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